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FOREST ECOSYSTEM RECOVERY IN 15-YEAR-OLD HYBRID ASPEN (*Populus tremula* L. × *P. tremuloides* Michx.) PLANTATIONS ON A RECLAIMED OIL SHALE QUARRY

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Abstract. *The development of forest ecosystem components (tree layer, understory vegetation and topsoil) in a reclaimed oil shale quarry was evaluated based on the repeated monitoring of sample plots 5 and 15 years after afforestation with hybrid aspen. Trees had been planted directly on levelled quarry spoil (site group A1) or on quarry spoil with restored topsoil (site group A2). The reference group included hybrid aspen plantations on former arable land (site group B1). Over a decade, the relative tree growth had been slower on A1 and A2 compared to B1. Soil reaction (pH_{KCl}) had decreased and soil total nitrogen (N_{tot}) had increased on A1. High pH_{KCl} value and low stocks of N_{tot}, phosphorus (P), manganese (Mn) and boron (B) restricted tree growth on A1. The properties of soil, as well as understory vegetation on A2 were similar to those on B1, which indicates that restored topsoil ensured the faster development of A2 towards the Hepatica forest type.*

Keywords: *Populus, oil shale quarry spoil, ecosystem restoration, total nitrogen, understory vegetation, bryophyte.*

1. Introduction

Afforestation is considered to be the best practice for ecosystem restoration on former opencast oil shale mining areas in Estonia because harsh soil conditions are rarely suitable for other land uses [1]. The increasing annual

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inputs of leaf and root litter, as well as permanent ground vegetation forming on skeletal quarry spoil could significantly increase soil organic matter pools and develop into the productive ecosystem during the first two to three decades after afforestation [2–5]. Since the 1960s, more than 10 000 ha of former opencast mining areas have been afforested in north-eastern Estonia [1] where Scots pine (*Pinus sylvestris* L.) has been the dominant tree species (> 90%) [1, 6].

Afforestation of post-mining oil shale quarries in Estonia is carried out directly on levelled quarry spoil, which is characterised as a calcareous skeletal detritus with a poor water holding capacity, low organic material supply, and limited nutrient availability [4, 7, 8]. Covering the levelled quarry spoil with previously removed topsoil is expensive, and is generally aimed at restoring land for agricultural use [9]. However, the reestablishment of topsoil cover can enhance revegetation and ecosystem restoration during the early stages of stand development, compared to bare quarry spoil [10, 11].

The main aim of degraded land restoration is to shorten the transitional time from overburden to self-functioning forest ecosystem [11]. Therefore, the choice of tree species for the afforestation of post-mining areas is an important factor that determines the duration of soil pedogenesis and successful forest ecosystem restoration [12, 13]. Monocultural pine stands are very prone to fire in dry quarry conditions, but fast-growing pioneer tree species like alders [5, 13] and birches [14–16] have several advantages over conifers in degraded land restoration. Deciduous trees have faster growth rates during early development [5, 17] and different fine root morphological adaptations [13, 15, 18]. The higher ameliorative potential of easily decomposable leaf litter [17, 19] could significantly influence soil biota abundance [20] and the faster accumulation of organic material [4].

Populus spp. have also successfully been used for post-mining areas restoration [21–23]. Poplars and their hybrids have been cultivated on a small scale on former quarry spoils in Estonia since the 1960s [14], and these attempts have shown that poplars can successfully be used if fast restoration is needed. For example, there are measurements from high productivity poplar stands on quarry spoil where the mean annual increment is more than 11 m^3 ha^{-1} yr^{-1}, at the age of 25 [10]. Hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) has a potential for the restoration of post-mining areas, in terms of fast growth at a young age [10, 24, 25] and its ameliorative impact on former arable soils during the first half of the rotation period [26]. However, so far experience with hybrid aspen on post-mining oil shale areas includes only the early development of the stands [10].

Nutrient availability for trees and nutrient supply in the long term are important factors in terms of successful ecosystem restoration and soil development on nutrient-poor post-mining quarry soils [3, 8]. It should be kept in mind that spoil material has a very low water holding capacity [8], which could seriously limit the growth of and nutrient uptake by trees.

Levelled quarry spoil creates nitrogen-limited conditions for trees [4, 8, 14], but several studies have shown that there is a clear positive impact of deciduous trees on soil nitrogen concentration in Estonian post-mining oil shale quarries [17, 19, 27]. The increase in nitrogen concentration is more clearly evident under N_2-fixing black alder plantation [17], but the abundance of N_2-fixing legume family species could also be an important source for nitrogen [28, 29].

The status of and changes in other important macronutrients are also essential in resource management and successful ecosystem restoration. For example, the available phosphorus (P) concentration is extremely low in quarry spoils [8, 14] and shows a clear decrease after post-mining quarry afforestation [17, 18]. The growth-controlling effects of P are evident during early development in post-mining soils [10, 21]. Generally, afforestation of former alkaline oil shale quarries under deciduous trees decreases soil acidity during the first decade [17], but sometimes the effect is more obvious after a longer period [18]. The status of and changes in soil micronutrients in post-mining quarries after afforestation have been studied more rarely [8, 23]. However, their importance to plant productivity and soil development cannot be neglected.

Successful restoration of deteriorated landscapes such as former mining areas includes also the recovery of floristic diversity. Restoration of the biodiversity that characterised the plant communities present in the period before mining is a time-consuming process. Even if the overall vegetation composition of reclaimed sites resembles that of the surrounding forest, a number of forest species may still be missing due to colonisation and recruitment problems [30, 31]. Studies of reclaimed Estonian oil shale and Czech coal mining sites have shown that different tree species have different impacts on the diversity and composition of understory [32–35].

So far, the impact of hybrid aspen plantations on the understory diversity on former mining areas has only briefly been studied in young stands [10], but the understory vegetation in older stands needs to be investigated as well. A study by Tullus et al. [36] of midterm-aged hybrid aspen plantations in former agricultural sites showed that hybrid aspen plantations host a rich understory flora where species with different ecological requirements are present, ranging from typical fallow species to shade-tolerant forest species. Studies of coal mine reclamation in the USA suggest that the species of herbaceous cover may be an important factor in forest establishment through both direct and indirect effects, and that the high diversity of ground cover may be beneficial for ecosystem development [37].

The main aim of this study is to assess the recovery of the forest ecosystem in 15-year-old (midterm) hybrid aspen plantations on a reclaimed oil shale quarry. The evaluation is based on repeated measurements of tree growth, understory vegetation (vascular plants and bryophytes), and the nutritional status of soil 5 and 15 years after afforestation. The study comprises mining sites subject to two different restoration methods: afforestation of bare quarry spoil (site group A1) and quarry spoil with restored topsoil (site group A2). Hybrid aspen plantations on former arable land with the prevailing soil type for the mining area (corresponding to the *Hepatica* forest site type) are used as a reference group (site group B1). The specific aims of the study are: 1) to clarify the effect of different restoration methods on 10-year changes in tree layer and soil nutritional status (soil reaction (pH_{KCl}), concentrations and stocks of macro- and micronutrients); 2) to determine tree-growth-limiting macro- and micronutrients at the midterm age; 3) to estimate how understory species affect mine soil properties, and to determine whether vegetation succession follows similar pathways in the two different quarry sites and whether plant communities on A1 and A2 converge or diverge over time. The hypotheses were: 1) ecosystem recovery has been faster on A2; 2) development of trees and understory vegetation has improved soil nutritional status on A1; 3) plantations in former mining sites support similar understory species richness and diversity to plantations in former agricultural sites.

2. Materials and methods

2.1. Study area

The study was carried out in two hybrid aspen plantations in Aidu oil shale quarry in north-eastern Estonia (Table 1). Both plantations were established in 2000 with a mixed planting of 1-year-old micropropagated clones of Finnish origin (C05-99-8 to C05-99-34) [10]. According to the nearest weather station (Jõhvi), the mean annual temperature was 5.5 ± 0.16 °C and the mean annual precipitation was 751 ± 31 mm during the time period from 2000 to 2014 (Estonian Environment Agency).

One hybrid aspen plantation in Aidu was directly planted on levelled quarry spoil (59°19′ N, 27°03′ E) where four sample plots (A1) were established [10]. The quarry overburden is a mixture of calcareous disintegrated Ordovician limestone and Quaternary sediments [4]. The second hybrid aspen plantation was planted on quarry spoil covered with previously removed topsoil (59°20′ N, 27°04′ E) where three sample plots (A2) were established [10]. The removed topsoil was stored in piles during the mining process and placed back on top of levelled quarry spoil at a depth of 40 to 60 cm [10].

For comparison, three sample plots (B1) of hybrid aspen plantations on former agricultural lands in northern Estonia were used [10] (Table 1). The soils of B1 are calcareous, drought-sensitive, automorphic soils, corresponding to the *Hepatica* forest site type [38], which will probably be the site type formed during the pedogenesis of former quarry sites [4].

Table 1. General overview of the studied 15-year-old hybrid aspen plantations on Aidu quarry and former arable soils

Plantation type	Plantation name	Site group	Plot	Soil type [39]	Density, trees·ha^{-1}	Basal area, m^2·ha^{-1}
Levelled quarry spoil	Aidu 1	A1	A1-1	*Calcaric Skeletic Regosol*	774	1.98
Levelled quarry spoil	Aidu 1	A1	A1-2	*Calcaric Skeletic Regosol*	652	0.83
Levelled quarry spoil	Aidu 1	A1	A1-3	*Calcaric Skeletic Regosol*	611	0.07
Levelled quarry spoil	Aidu 1	A1	A1-4	*Calcaric Skeletic Regosol*	754	3.17
Restored soil on quarry debris	Aidu 2	A2	A2-1	Mixture of *Calcaric Cambisol*	448	5.96
Restored soil on quarry debris	Aidu 2	A2	A2-2	Mixture of *Calcaric Cambisol*	326	3.84
Restored soil on quarry debris	Aidu 2	A2	A2-3	Mixture of *Calcaric Cambisol*	285	2.91
Former agricultural soil	Sõeru	B1	B1-1	*Calcaric Skeletic Luvic Rendzic Phaeozem*	1070	17.57
Former agricultural soil	Sõeru	B1	B1-2	*Calcaric Rendzic Skeletic Leptosol*	1180	9.97
Former agricultural soil	Mikkeri	B1	B1-3	*Calcaric Endoleptic Cambisol*	700	3.65

2.2. Tree growth measurement

Tree growth measurements in 15-year-old plantations on quarries were carried out on the same 12.5 m radius circular experimental plots that were subjected to measurements at the age of 5 [10]. The stem diameter at breast height over bark (DBH, cm) was recorded for every single tree with a millimetre-scale standard forest calliper. The height of every tree was measured with a telescopic measuring rod for trees smaller than 8 m. Trees over 8 m were measured with a Vertex IV (Haglöf Sweden AB) with 0.1 m resolution.

Single tree volumes were calculated using Johnsson's equation [40]:

$$V = 0.03186 \times DBH^2 \times H + 0.43 \times H + 0.0551 \times DBH^2 - 0.4148 \times DBH, \quad (1)$$

where V is single tree stem volume, dm^3; DBH is stem diameter at breast height, cm; and H is tree height, m.

2.3. Soil analysis

The soil sampling in 15-year-old hybrid aspen plantations was carried out using the same methods as in an earlier survey [10]. Soil samples were taken systematically all over the sample plot and mixed together as a composite sample from both quarry sites. On levelled quarry detritus, the fine earth fractions between rock debris were collected. On levelled quarry spoil covered with previously removed soil, soil samples were taken from the 0–20 cm topsoil layer. Soil analysis for former arable land plantations was described by Lutter et al. [26] who used data about the 0–20 cm soil layer. The same was used in the current study.

For determination of soil pH_{KCl}, a 1 M KCl suspension in the ratio of 10 g : 25 ml was used. The total nitrogen (N_{tot}) was determined according to Kjeldahl (ISO 11261:1995) [41]. The available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu) and manganese (Mn) were determined using the Mehlich method [42]. The available boron (B) was determined employing the hot-water extraction procedure [43].

Total nutrient stocks were calculated for the 0–20 cm soil layer by multiplying the nutrient concentration by the soil bulk density [44] and soil layer volume, from where the content of debris was subtracted [4]. All soil chemical analyses were carried out in the Laboratory of the Agricultural Research Centre in Saku (http://pmk.agri.ee/) (Table 2).

Data about pH_{KCl}, N_{tot}, P and K gathered during the earlier soil survey has been presented by Tullus et al. [10]. The rest of the data about 5-year-old quarry soils was collected within the framework of the same survey, but has not been previously published.

Table 2. Chemical properties of soil of the studied sample plots in 15-year-old plantations

Plantation name	Site group	Plot	pH_{KCl}	N_{tot}, %	P, mg·kg^{-1}	K, mg·kg^{-1}	Ca, mg·kg^{-1}	Mg, mg·kg^{-1}	Cu, mg·kg^{-1}	Mn, mg·kg^{-1}	B, mg·kg^{-1}
Aidu 1	A1	A1-1	7.4	0.11	13	123	7373	99	3.3	38	0.33
Aidu 1	A1	A1-2	7.4	0.10	5	98	15520	150	1.0	28	0.54
Aidu 1	A1	A1-3	7.8	0.06	1	37	38135	211	0.3	22	0.27
Aidu 1	A1	A1-4	7.6	0.23	4	468	29693	1050	0.7	31	1.77
Aidu 2	A2	A2-1	7.0	0.25	126	232	4867	108	2.2	229	1.58
Aidu 2	A2	A2-2	7.1	0.35	189	104	6401	89	2.7	42	1.71
Aidu 2	A2	A2-3	7.3	0.28	39	110	6744	162	2.1	41	1.77
Sõeru	B1	B1-1	7.3	0.25	151	373	6506	220	2.8	55	2.13
Sõeru	B1	B1-2	7.1	0.19	48	163	3238	160	1.3	196	1.02
Mikkeri	B1	B1-3	7.3	0.22	44	119	4125	246	1.2	180	1.00

2.4. Floristic data

Floristic data were collected about permanent vegetation plots established at a young age (each 2 × 2 m in size, four in each study plot) [10]. For every vegetation plot a list of vascular plant and bryophyte species was compiled. The total percentage cover of the field and bryophyte layers and the percentage cover of individual species were estimated. In addition, a list of bryophyte species growing on the trunks of four trees situated near the vegetation plot corners was compiled. Data about bryophytes that could not be identified in field conditions were collected for further microscopic investigations. The nomenclature followed The Handbook of Estonian Vascular Plants [45] and Annotated checklist of Estonian bryophytes [46].

To characterise the understory species of hybrid aspen plantations, all vascular plants were classified by habitat preference based on The Handbook of Estonian Vascular Plants [45]. All bryophytes recorded in the plantations were classified as follows: short-lived species or perennial species, based on Dierβen [47].

2.5. Statistical analyses

A pairwise Student's *t*-test was used to determine the significance of differences in soil nutrient concentrations and pH_{KCl} between the first and second monitorings. One-way ANOVA, followed by the Tukey LSD test, was used to determine significant differences in soil nutrient stocks and pH_{KCl} between the studied sites, to clarify the effects of growth characteristics (tree height and plantations basal area) and *Fabaceae* species cover on N_{tot} concentration changes. Available P and Mn stocks were log-transformed in order to meet assumptions of the homoscedasticity and normal distribution of the residuals in the soil nutrient stocks comparison. The impact of soil pH_{KCl} and nutrient stocks on tree height growth in midterm plantations were analysed using a non-linear regression model.

Species richness (*S*) and Simpson's diversity index (*D*') were estimated for vegetation plots with PC-ORD Version 6 [48] according to Equations (2) and (3):

$$S = n, \quad (2)$$

$$D' = 1 - \sum_{i=1}^{n} p_i^2, \quad (3)$$

where n is the number of species present in the vegetation plot, and p_i is the proportion of the sample belonging to the ith species. Variation in species composition was investigated with non-metric multidimensional scaling (NMDS) using the community ecology package Vegan in R [49]. NMDS was run with the "metaMDS" function and Bray-Curtis dissimilarities. Environmental variables were fitted onto the ordination using the function "envfit". To compare species composition between plantation types and assess the corresponding associations, Multiresponse Permutation Procedures (MRPP) and Indicator Species Analysis (ISA) were performed with PC-ORD 6. To correct the *p*-values for multiple comparisons in MRPP, the Bonferroni correction was applied. NMDS, MRPP and ISA were run with study-plot-level data, using the averaged vascular plants and ground-inhabiting bryophytes cover values for four vegetation plots.

A linear mixed model with R Statistics [50] function "lmer" in package lme4 (with sample plot as a random variable) was applied to clarify the plantation type effect on single tree growth characteristics and to clarify the plantation type effect on vegetation-plot-level estimates of vascular plant, bryophyte and *Fabaceae* species. The Tukey LSD test was applied if a statistically significant plantation type effect was observed to compare the group means.

Mean values are presented with standard error. The normality of the variables was tested with the Shapiro-Wilk test. Q-Q plots and residual distributions were used to assess the normality of model residuals. A level of significance of $\alpha = 0.05$ was used to reject the null hypothesis after statistical tests.

3. Results and discussion

3.1. Tree growth

In 15-year-old hybrid aspen plantations, the mean tree height on bare levelled quarry spoil (A1) (5.4 ± 0.24 m) was significantly lower ($p = 0.001$) compared to reference (B1) sites on former agricultural land (13.6 ± 0.24 m). In contrast to preliminary observations at the age of 5 years [10], height growth on A1 did not differ ($p = 0.096$) any more from that on quarry spoil with restored topsoil (A2) where the mean height was 10.0 ± 0.30 m (Fig. 1a). The significant difference between A1 and A2 persisted in the mean DBH (Fig. 1b) and single tree stem volume (Fig. 1c). Hybrid aspen height growth on A1 (5.4 m) exceeded that of same-aged Scots pine stands planted directly on quarry spoil (varying from 2.0 to 4.0 m) [1, 2, 19], and is similar to the results obtained in black alder and silver birch plantations (2.5 to 6 m) on stony quarry spoil of similar age class (10–12 years) [1, 14].

Compared to former arable land plantations (B1 = 100%), the relative tree height had dropped on both quarry sites (from 58 to 40% on A1 and from 100 to 74% on A2) during the 10-year period (Fig. 1a). In addition to low nutrient pools on A1 (Fig. 2), the inhibited growth on quarry sites, compared to former arable soils, may be probably explained by a limited soil water supply [51]. The soil water supply on quarry soils depends mainly on precipitation, as beneath topsoil there is skeletal material which lacks capillary groundwater support. The initially faster tree growth on A2 was because of a finer soil texture and better nutritional conditions compared to bare levelled spoil [10]. However, the layering of cover material with different textures creates interfaces that can influence the field capacity of soil moisture [52]. One possibility for improving the productivity of hybrid aspen plantations on drought sensitive quarry spoil is to select genotypes whose water use efficiency is higher in dry conditions, as suggested by Bungart and Hüttl [22] for poplars on lignite mining areas in Germany.

The density of trees during the last 10-year period in the studied quarry sites has remained at a similar level, except on A1, where the mortality was 15% (Fig. 1d). Hybrid aspen tree density in the studied quarry sites (A1 = 698 and A2 = 353 trees per ha) is lower compared to other studies where tree density varies from around 1600 to 2300 trees per ha at the age of 30, for planted deciduous trees [17, 18]. Moreover, on A2 the density is already below 400 trees per ha, which is recommended for hybrid aspens at the maturity age of 25 years [25]. A low tree density could hamper soil

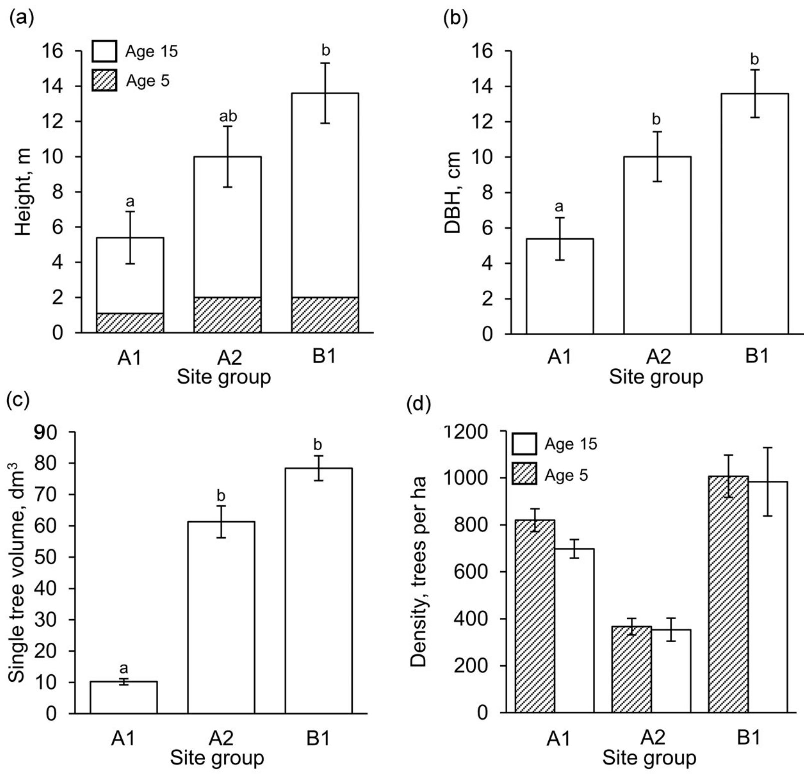

Fig. 1. A comparison of hybrid aspen mean growth characteristics (a, b, c) and tree density (d) in different plantation types (levelled quarry spoil – site group A1; levelled quarry spoil with restored topsoil – site group A2; former arable soil – site group B1) at the age of 15. Whiskers denote standard error. Letters denote significant differences between site groups according to the Tukey LSD test.

development through low inputs of leaf and root litter. Moreover, dense light-demanding herbaceous ground vegetation could be promoted by a sparse tree layer and inhibit or delay the success of forest establishment by competing for soil resources with young trees [37].

3.2. Soil reaction and nutrients status

At the age of 15, the 0–20 cm topsoil reaction (pH_{KCl}) and stocks of several macro- and micronutrients were significantly lower under hybrid aspen plantations on bare quarry spoil (A1) compared to quarry spoil with restored topsoil (A2) and former agricultural land (B1) (Fig. 2). However, over the 10-year period soil chemical characteristics in the studied sites showed only slight changes (Table 3). In nutrient-limited conditions plants start to invest the obtained resources into root expansions, and above-ground production will be retarded [53].

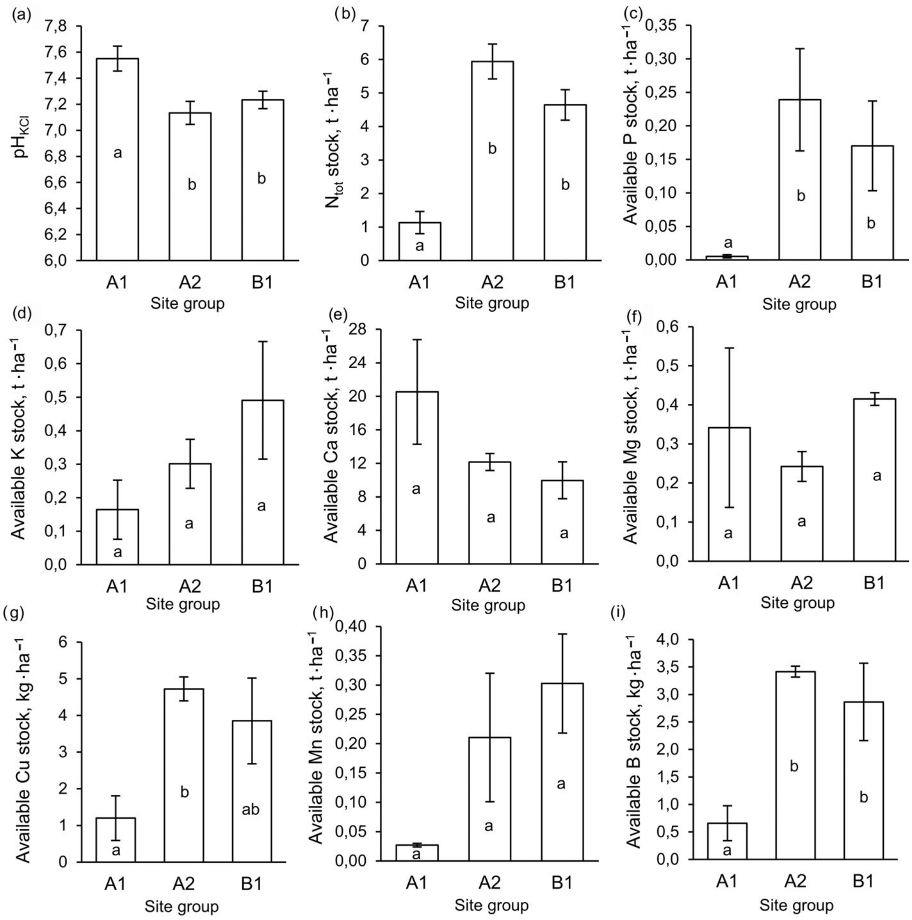

Fig. 2. A comparison of soil pH_{KCl} and available nutrient stocks in the 0–20 cm soil layer between different plantation types (levelled quarry spoil – site group A1; levelled quarry spoil with restored topsoil – site group A2; former arable soil – site group B1) at the age of 15. Whiskers denote standard error. Letters denote significant differences between site groups according to the Tukey LSD test.

Soil reaction (pH_{KCl}) had decreased according to a one-sided hypothesis ($p = 0.030$) by –0.32 units to 7.55 ± 0.09 on site group A1 (Table 3). In spite of its decrease on A1 and non-change on A2 and B1, pH_{KCl} was still significantly higher on A1 than on A2 and B1 (Fig. 2a). A similar result was also found at the age of 15 [10]. Several studies report that deciduous trees are able to decrease soil reaction much faster in alkaline post-mining quarry sites when compared with conifers with easily decomposable plant litter and acid root exudates [17, 18]. After afforestation of quarry spoil (A1), the calcareous fragments of spoil material are expected to weather, with decarbonisation as a consequence. Superficial leaching is expected to occur,

Table 3. Absolute and relative changes of soil pH_{KCl} and available nutrient concentrations in 5- to 15-year-old plantations (levelled quarry spoil – site group A1; levelled quarry spoil with restored topsoil – site group A2; former arable soil – site group B1)

Soil property	A1			A2			B1		
	Abs. change	Rel. change, %	One-tailed *p*-value	Abs. change	Rel. change, %	One-tailed *p*-value	Abs. change	Rel. change, %	One-tailed *p*-value
pH_{KCl}	–0.32	–114*	0.030	–0.03	–10	0.211	+0.07	13	0.346
P, $mg \cdot kg^{-1}$	–4	–39	0.177	10	9	0.400	7	9	0.086
K, $mg \cdot kg^{-1}$	103	130	0.134	62	72	0.062	–37	–14	0.102
Ca, $mg \cdot kg^{-1}$	–4042	–15	0.359	–16	0	0.465	–644	–12	0.177
Mg, $mg \cdot kg^{-1}$	131	53	0.298	2	2	0.299	21	11	0.356
Cu, $mg \cdot kg^{-1}$	–0.85	–39	0.144	+0.07	3	0.211	+0.12	7	0.270
Mn, $mg \cdot kg^{-1}$	–3	–10	0.054	17	20	0.148	24	20	0.168
B, $mg \cdot kg^{-1}$	+0.198	37	0.232	–0.170	–9	0.002	–0.323	–19	0.039
N_{tot}, %	+0.070	127	0.058	+0.023	9	0.148	+0.004	2	0.409

* The relative change of H+ considers the logarithmic scale of pH. The abbreviations used: Abs. – Absolute; Rel. – Relative.

soil fine material content will increase, and Ca-bound nutrients will be released [54]. High soil reaction is hampering tree growth in the studied sites at the age of 15 (Fig. 3a). Similar effects have also been reported for silver birch plantations on quarry spoil during the first decade [17, 18] where pH stabilisation was observed after three decades [18]. The negative impact of high soil reaction was also observed in young hybrid aspen plantations on former arable land, although this effect disappeared at the midterm age [55] along with decreased pH_{KCl} [26].

The stock of N_{tot} on A1 was significantly lower compared to A2 and B1 (Fig. 2b). A low stock of N_{tot} also showed a growth-controlling effect on A1 (Fig. 3b), as seen at the young age [10]. However, during the period from young to midterm age, a marginally significant increase in N_{tot} concentration (+127%) had occurred on A1. The change of N_{tot} concentration on A1 had a significant positive relationship with the cover of N_2-fixing *Fabaceae* family species and tree growth characteristics (Table 4). The positive impact of tree growth on the N_{tot} concentration increase means that higher amounts of litter inputs positively influence soil development. A positive relationship between stand age and increasing amounts of plant litter in terms of N_{tot} increase has also been observed for silver birch in less than a decade following afforestation [17, 18] and over a longer period of time for Scots pine [19]. N_2-fixing alders can cause N_{tot} increase in less than a decade following planting [17], and high concentrations could remain even after several decades [33]. The results presented here demonstrate that the presence of N_2-fixing *Fabaceae* species in understory vegetation also plays an important role in soil development by increasing soil nitrogen storage (Table 4). For example, the rates of symbiotic N_2-fixing legumes vary with plant species, growing season and soil fertility, but are commonly between 100 and 300 kg·ha^{-1}·yr^{-1} [28]. The presence of legume species in the studied sites was spontaneous, but the sowing of legume species could be an effective approach to improving soil nitrogen status on N-deficient post-mining areas, being also environmentally friendlier than fertilisation [29, 37]. On the other hand, a vigorous herbaceous cover could inhibit the natural regeneration of trees, or cause high mortality and a growth-hampering effect on young tree seedlings [37].

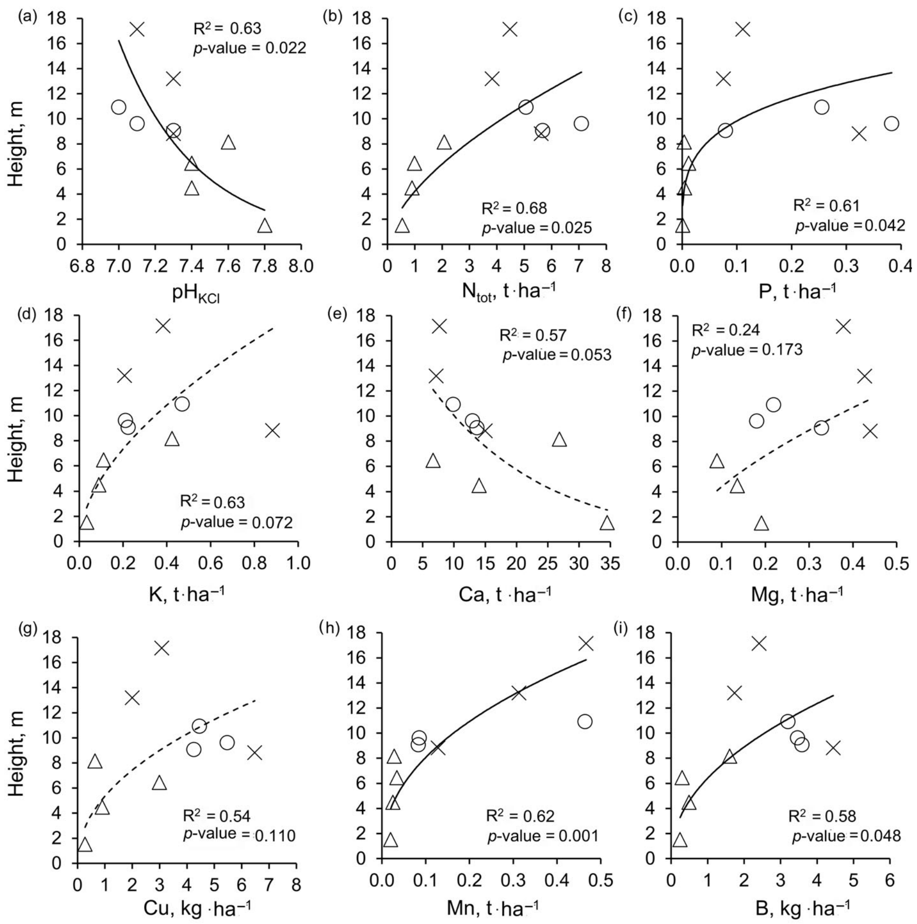

Fig. 3. Non-linear relationships between plot mean tree height and soil chemical properties (pH_{KCl} and nutrient pools) in the studied 15-year-old hybrid aspen plantations. Triangles refer to site group A1, circles to site group A2 and crosses to site group B1. Broken lines indicate insignificant relations.

Table 4. The regression slopes between soil total nitrogen concentration changes and *Fabaceae* species cover and tree growth characteristics (height and basal area) in the studied quarry sites

Factor	Site group	ΔN_{tot} concentration, %	
		Estimate	*p*-value
Cover of *Fabaceae*, %	A1	0.74 ± 0.18	0.001
	A2	–0.51 ± 0.65	0.950
Height, m	A1	0.90 ± 0.19	< 0.001
	A2	0.73 ± 0.22	0.007
Basal area, $m^2 \cdot ha^{-1}$	A1	0.94 ± 0.09	< 0.001
	A2	0.73 ± 0.21	0.007

Note: ΔN_{tot} – total nitrogen concentration changes. All variables were scaled in order to compare the magnitude of effects.

The studied calcareous quarry spoil (A1) also has a very low available P supply compared to A2 and B1 (Fig. 2c). As soil reaction still remained higher than the optimum level (Fig. 2), the P stock remained unchanged compared to the young age on A1 (Table 3). At the same time, studies with other tree species have reported a decrease of P on post-mining quarry spoils under Scots pine, silver birch and black alder in less than a decade following planting [17, 18]. The availability of P next to a low N supply was controlling tree growth in young hybrid aspen plantations on A1 [10], and this influence continued at the midterm age (Fig. 3c). P is also reported as a growth-limiting factor in young black alder, silver birch and Scots pine plantations at the young age on quarry spoil in Estonia [38], but also on afforested post-mining areas, according to some studies [22, 56]. P fertilisation, along with N and K, is recommended on post-mining lignite poplar plantations after eight years [22]. Even though available K showed significant stock differences between two former quarry sites (Fig. 2), no influence of available K on tree growth was detected.

Regarding micronutrients, significantly lower available Cu, Mn and B stocks were observed on A1 compared to A2 and B1 (Fig. 2g–i). B and Cu are considered to be the most deficient micronutrients in quarry spoil substrate to trees, according to an earlier study in Estonia [8]. During the 10-year period, available B concentration on A2 had significantly decreased, by –9% ($p = 0.002$), and on B1, by –20% ($p = 0.039$). The decline of B in the A horizon was also observed in hybrid aspen plantations on former arable lands representing a wider range of soil types during the same age period [26]. The decline of available B was greater in plantations with faster tree growth [26], but B could easily be lost through the leaching after a pH drop [57]. B stocks on A2 and B1 were still high, and were not limiting tree growth (Fig. 3i), but low stocks of available B and Mn had a growth-controlling effect on A1 (Fig. 3h–i). Generally, Mn deficiency occurs on highly calcareous soils: for example, the Mn concentration in tree leaves showed a strong negative relationship with soil pH [58]. An early study of white pine (*Pinus* *strobus* L.) growth on reclaimed strip mines showed that Mn was the second important nutrient, besides P, to explain growth variability [56].

The long-term storage of topsoil in stockpiles during the mining process could significantly and adversely alter the biological, physical and chemical properties of soil for plants [59]. At the same time, afforestation with hybrid aspen has not caused any further substantial changes in the chemical properties of restored topsoil. No differences in pH_{KCl} and nutrient stocks between A2 and B1 were found 15 years after afforestation, indicating that the soil characteristics of site group A2 are similar to those of the dry *Hepatica* forest site type [38] forming on B1 after the afforestation of former calcareous arable lands. A sporadic humus layer, low fine material content and easily desiccating soil conditions suggest that the afforestation of A1 has promoted the restoration of *Rendzic* soils [38, 39].

3.3. Floristic diversity and changes

Altogether 96 vascular plant species and 27 bryophyte species were found in the three plantation types, which is considerably more than the respective figures of 75 and 12 recorded at a young age. The overall species richness of vascular plants and bryophytes had increased in all plantation types, following a similar trend to that observed in midterm hybrid aspen plantations on former agricultural land [36]. While no bryophyte species were found on tree trunks or tree bases in young plantations, the bryoflora of midterm plantations contained epiphytic species as well. All vascular plant and bryophyte species recorded in the studied stands were common species.

MRPP tests revealed significant differences in the understory species composition between plantations on A1 and A2 (p = 0.009) and between plantations on A1 and B1 (p = 0.010), whereas the comparison of understory species composition between A2 and B1 revealed no differences (p = 0.117).

Compositional differences between plantation types were confirmed by NMDS ordination, as the plantation type significantly affected the position of study plots in the ordination space (Table 5, Fig. 4a). In addition, variation in species composition was significantly affected by the density and basal area of overstory trees, availability of N, P, Cu and B in the soil humus horizon, and by soil pH. The strong effect of soil conditions on understory has been observed in a number of studies analysing vegetation assemblages in post-mining sites [34, 60].

Despite the compositional differences, the species richness and diversity of vascular plants per vegetation plot were similar in all plantation types, whereas the cover of the field layer was significantly lower on A1 (Table 6), similarly to the results obtained for young stands earlier [10]. In addition, all plantation types were dominated by species belonging to similar ecological groups, i.e. light-demanding grassland species. The results of indicator species analysis also showed that grassland species were characteristic of all plantation types; for example, *Agrostis capillaris* L., *Erigeron acer* L. and

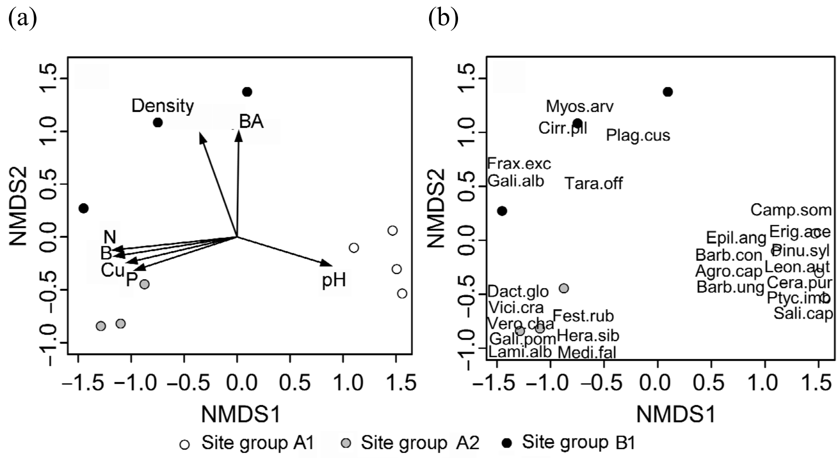

Fig. 4. NMDS ordination of study plots (stress 0.06). The arrows in Fig. 4a indicate environmental vectors that were significantly related ($p < 0.05$) to ordination (see also Table 5). Species that, according to indicator species analysis, were characteristic of plantations on site group A1, A2 or B1 are shown in Fig. 4b. Species abbreviations: Agro cap – *Agrostis capillaris*; Dact glo – *Dactylis glomerata*; Epil ang – *Epilobium angustifolium*; Erig ace – *Erigeron acer*; Fest rub – *Festuca rubra*; Frax exc – *Fraxinus excelsior*; Gali alb – *Galium album*; Gali pom – *Galium* × *pomeranicum*; Hera sib – *Heracleum sibiricum*; Lami alb – *Lamium album*; Leon aut – *Leontodon autumnalis*; Medi fal – *Medicago falcata*; Myos arv – *Myosotis arvensis*; Pinu syl – *Pinus sylvestris*; Sali cap – *Salix caprea*; Tara off – *Taraxacum officinale* (coll.); Vero cha – *Veronica chamaedrys*; Vici cra – *Vicia cracca*; Barb con – *Barbula convoluta*; Barb ung – *Barbula unguiculata*; Camp som – *Campylidium sommerfeltii*; Cera pur – *Ceratodon purpureus*; Cirr pil – *Cirriphyllum piliferum*; Plag cus – *Plagiomnium cuspidatum*; Ptyc imb – *Ptychostomum imbricatulum*.

Table 5. Relationships between vascular plants and bryophyte species composition (NMDS ordination, Fig. 4a) and environmental variables

Environmental factor	r^2*	*p*-value
Density of trees	0.75	0.003
Basal area	0.69	0.007
N_{tot} stock	0.96	0.001
Available P stock	0.71	0.020
Available K stock	0.42	0.150
Available Ca stock	0.35	0.204
Available Mg stock	0.07	0.838
Available Cu stock	0.78	0.006
Available Mn stock	0.52	0.074
Available B stock	0.94	0.001
Soil pH_{KCl}	0.59	0.032
Plantation type	0.88	0.001

* The r^2 values show the squared correlation coefficient for the environmental factors fit onto the NMDS ordination; *p*-values are based on random permutations of the data.

Leontodon autumnalis L. were typical of A1; *Dactylis glomerata* L., *Festuca rubra* L., *Galium* × *pomeranicum* Retz., *Heracleum sibiricum* L., *Medicago falcata* L., *Veronica chamaedrys* L. and *Vicia cracca* L., of A2; and *Galium album* Mill., of B1 (Fig. 4b).

These results are in accordance with those obtained by Mudrak et al. [34] who found that grassland species were the most common group of understory plants in 22- to 33-year-old plantations on spoil heaps in Czechia, explaining this by the availability of light and proximity to grasslands as seed sources. The same factors are probably responsible for the dominance of grassland species established in the current study. Typical forest understory species were only sparsely represented in the field layer, while their number was significantly higher in the stands located on former agricultural lands (Table 6). At the same time, the understory on B1 differed from that of quarry sites by a higher number of fallow species, due to the effect of the formerly agricultural land use, which agrees with the results of earlier studies that have demonstrated the long-term impact of former land use on understory species composition in plantations [61, 62]. The number of ground-dwelling bryophytes was the greatest and the coverage of the bryophyte layer the highest on B1, followed by A1, where the abundance of short-lived bryophyte species was high. The dominance of short-lived species on A1 was also illustrated by an indicator species analysis that pointed out *Barbula convoluta* Hedw, *B. unguiculata* Hedw., *Ptychostomum imbricatulum* (Müll.Hal) D.T.Holyoak & N.Pedersen and *Ceratodon*

Table 6. Vegetation plot mean values (± SE) of and plantation type effect on the characteristics of vascular plant and bryophyte species in midterm plantations

Vegetation characteristic	Site group			Plantation type effect, *p*-value
	A1	A2	B1	
S_vascular plants	13.9 ± 1.2	16.9 ± 1.4	18.7 ± 1.4	0.090
*D'*_vascular plants	0.86 ± 0.02	0.84 ± 0.02	0.86 ± 0.02	0.623
C_field layer	25.4 ± 6.5a	70.3 ± 7.5b	59.0 ± 7.5b	0.006
S_trees and shrubs	3.4 ± 0.5b	0.8 ± 0.6a	1.7 ± 0.6ab	0.044
S_forest species	0.8 ± 0.2a	0.3 ± 0.2a	1.5 ± 0.2b	< 0.001
S_grassland species	6.6 ± 1.1	11.8 ± 1.3	9.1 ± 1.3	0.054
S_fallow species	2.9 ± 0.5a	4.1 ± 0.6a	6.2 ± 0.6b	0.013
S_bryophytes_ground	4.8 ± 0.7b	1.4 ± 0.8a	5.3 ± 0.8b	0.021
*D'*_bryophytes_ground	0.62 ± 0.07b	0.15 ± 0.08a	0.47 ± 0.08b	0.009
C_bryophyte layer	15.5 ± 8.1a	9.9 ± 9.3a	48.3 ± 9.3b	0.043
S_short-lived bryophytes	2.8 ± 0.3b	0.8 ± 0.4a	1.5 ± 0.4a	0.015
S_perennial bryophytes	2.0 ± 0.6ab	0.6 ± 0.6a	3.8 ± 0.6b	0.026
S_bryophytes_trunk	0.3 ± 0.6a	3.5 ± 0.6b	2.3 ± 0.6b	0.018

Note: Letters denote significant differences between site groups according to the Tukey LSD test. The symbols used: S – species richness (number of species per vegetation plot); *D'* – Simpson's diversity index (values vary between 0 and 1); C = cover, %; SE – standard error.

purpureus (Hedw.) Brid. as characteristic bryophyte species (Fig. 4b). These bryophytes are all pioneer species typical of early successional series, representing a colonist life strategy as they produce large quantities of small spores, and are able to disperse long distances.

One aim of the current study was to determine whether plant communities on A1 and A2 converge or diverge over time. Concerning the vascular plants, no clear trends towards convergence or divergence could be observed as the comparison of vegetation characteristics between the two plantation types gave similar results at the time of both monitoring periods (based on the pair-wise Student's *t*-test, data not shown). Despite the spatial vicinity between plantations on A1 and A2, only seven vascular plant species were common to both plantation types at the young age, whereas the total number of species recorded on A1 and A2 was 54. In midterm plantations, nine vascular plant species were common to both plantation types out of the 61 recorded species. In the case of bryophytes, there was a tendency towards divergence as the species richness and diversity of ground-dwelling bryophytes were significantly higher on A1 at the midterm age due to the higher number of short-lived bryophytes. On A2 the high coverage of the field layer (Table 6) probably inhibited the recruitment of short-lived bryophyte species, while on levelled quarry spoil their light spores could spread easily.

4. Conclusions

Repeated monitoring of the main forest ecosystem components (tree growth, soil properties and understory plant cover) was carried out to describe ecosystem recovery on a reclaimed oil shale quarry.

During the 10-year development from young to midterm age, the relative height growth of hybrid aspen on bare quarry spoil and on spoil covered by restored topsoil was slower than on former arable *Cambisol*. On levelled quarry spoil, pH_{KCl} had decreased, N_{tot} had increased and other macro- and micronutrients had remained unchanged. The marginal increase of N_{tot} on quarry spoil was positively related to the cover of *Fabaceae* species and tree growth. Available B had decreased on quarry spoil covered with previously removed topsoil. In addition to dry conditions, tree growth on bare quarry spoil was limited by low stocks of N_{tot}, P, B and Mn.

The compositional differences that were observed at the young age in the understory vegetation of the quarry sites representing two different restoration methods persisted, and were evident in the midterm plantations as well. Generally, hybrid aspen plantations in former mining sites support the similar understory species richness to that in plantations in former agricultural sites and, regardless of plantation type, understory is dominated by light-demanding grassland species.

In conclusion, hybrid aspen is a prospective tree species for the restoration of post-mining landscapes. Generally, soil recovery and tree growth 15 years after restoration of quarry spoil with hybrid aspen are similar to those upon afforestation with other fast-growing deciduous trees such as black alder and silver birch, but faster than Scots pine. However, complete restoration of a forest ecosystem is a long-term process, which cannot be achieved in 15 years, therefore monitoring of these sites should be continued.

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